# Suppression of telegraph noise in a CPP spin valve by an oscillating spin torque: Numerical study

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## Abstract

The phenomenon of stochastic resonance (SR) has been mainly studied in one-dimensional systems with additive noise. We show that in higher dimensional systems and in the presence of multiplicative noise, a non-linear magnetic system with a strongly periodic current can show behavior similar to that of SR but only for frequencies below the ferromagnetic resonance (FMR) frequency of the system. Such a phenomena can provide an effective way to suppress low frequency noise in spin valve magnetic sensors.

The application of stochastic resonance[1] to increase the signal to noise ratio (SNR) is now well established in many physical systems[2] and has also been shown to increase the stability of an unstable system in some cases[3]. Particle production in a quantum field can also be enhanced in the presence of noise[4]. The SNR is enhanced by adding noise to the system as it is being driven by an external periodic force. However until now only one-dimensional systems with additive noise and a simple bistable potential, e.g., $U(x) = x^4 - x^2$, or a potential with one metastable state, e.g., $U(x) = x^3 - x^2$, have been studied and shown to have this interesting property of increasing the SNR with the addition of noise as it is being driven by a time-dependent force. This counter intuitive response is inherently related to the non-linearities present in these systems. One might therefore ask if a similar behavior can be found in more complicated systems, in particular magnetic systems. In this letter, we give one example of such systems; a spin valve of two magnetic layers separated by a normal conductor. The magnetization is inhomogeneous in the 'free' layer and a current perpendicular to the plane (CPP) traverses the structure. In this case a spin torque between the layers can exist and will play in the following an important role in the SR effect.

Until recently, the ideas of stochastic resonance have not been exploited in magnetic systems. As far as I know, reference[5] provides the only application we are aware of; it applies SR to the measurement of hysteresis loops in magnetic systems described by Preisach model. In the following, we study a magnetic system with multiplicative noise and show that a stochastic resonance type behavior exist in this system and can be taken advantage of to *selectively* suppress frequencies from the noise spectrum. The system we treat is very realistic and hence more complex than previously treated systems[2]. The use of strong time-dependent currents implies that our system is in a non-equilibrium state and linear response methods are obsolete for our study[6]. In this letter we will attempt only a qualitative treatment of this subject aided by numerical integration of the non-linear Landau-Lifshitz-Gilbert equation[7].

We study a current perpendicular to the plane (CPP) spin valve with two magnetic layers (fig. 1), one with magnetization $\mathbf{S}_p$ pinned along the x-axis (reference layer RL) while the other layer (FL) has a free magnetization $\mathbf{S}_f$. Figure 2 shows the power spectral densities (PSD) of the thre components of the magnetization in the absence of current. The PSD's have been normalized the same way in all the figures. The noise in the z component is smallest due to the demagnetization field. The current has an ac component in addition to

the dc component. The source of noise in the system is due to thermal fluctuations that activates switching between two states and hence it is intrinsic to the system. To get an energy surface with more than one local minimum, we bias the spin valve with an external field that is close to being perpendicular to the fixed magnetization of the RL and take into account spin momentum transfer effects[8] between the two layers of the spin valve. The y-component of the external field is kept at 600 $Oe$ while the one along $\mathbf{S}_p$ is kept around $-100\ Oe$. The layers have dimensions $100 \times 100 \times 3\ nm^3$ with the easy axis along the x-axis and anisotropy $H_k = 50\ Oe$. The magnetization in the pinned layer is fixed by a large bias field. Hence, in this study the pinned layer is studied micromagnetically on equal footing with the free layer. The magnetization in this structure shows two configurations (Fig. 3) which are non-homogeneous and are a result of the demagnetization field, the current field and any interaction between the layers[9]. In addition to stable and unstable states, the system has saddle points which are present due to the spin torque term. Spin valve structures are useful components of giant magneto-resistance (GMR) sensor devices and hence the manifestations of stochastic resonance in these systems may be of practical importance. To increase the sensitivity of a GMR sensor, the bias field on the free layer is almost perpendicular to the magnetization of the pinned layer. It is this kind of biasing that gives rise to the $1/f$-type noise studied here since it permits the system to hop between two-states. The results reported here are valid even if the pinning of the bottom layer is not perfect. In fact, large bias fields tend to 'distort' the magnetization in the pinned layer but only slightly and will not contribute to the 1/f-type noise observed here.
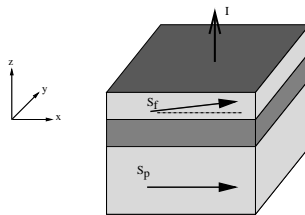


FIG. 1: The tri-layer geometry of the spin valve described in this work. The bottom magnetic layer is supposed to be very thick and is pinned along the x-axis. The top layer is also magnetic but free. Both layers are separated by a thin 0.8 $nm$ normal conductor and traversed by an ac and a dc current as shown.

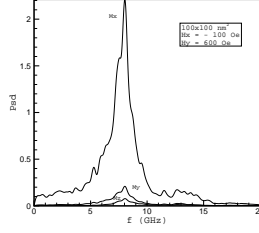To analyze this system, we use the Landau-Lifshitz-Gilbert equation[7] supplemented by

FIG. 2: Spectral densities (in arbitrary units) at zero current of the different components of the magnetization. The FMR peak of the system is around $7.0\,GHz$ in the absence of a spin torque.
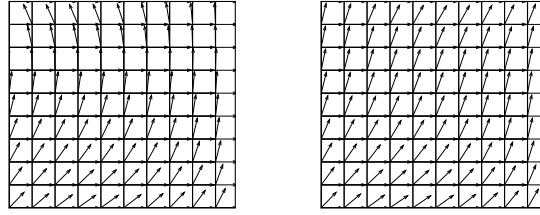


FIG. 3: The two metastable states exhibited by the spin valve system at room temperature: a 'C' state and a 'S' state. The horizontal arrows are those of the magnetization of the bottom layer which points along the x-axis.

the spin torque as first suggested by Slonczweski[8],

$$
\begin{aligned}
\frac{d\,\mathbf{M}}{d\,t} &= -|\gamma|\mathbf{M} \times \Big(\mathbf{H}_{eff} + \mathbf{h}(t) \\
&\quad + p\frac{I_s}{M_s}\left(\mathbf{M} \times \mathbf{m}_{ref}\right) - \frac{\alpha}{|\gamma|M_s}\frac{d\,\mathbf{M}}{d\,t}\Big)
\end{aligned}
\tag{1}
$$

where $\gamma$ is the gyromagnetic ratio and $\alpha$ is the damping constant taken here to be equal to 0.01. The effective field $\mathbf{H}_{eff}$ includes exchange interactions, anisotropy, the demagnetization field and the field from the current. The interlayer exchange is assumed small of the order of $20\,Oe$. The value of $\alpha$ chosen is larger than typical values of damping in the bulk of a Permalloy. In a geometry such as ours, the damping is dominated by interfacial damping and 0.01 is a reasonable value for it[10]. The noise is assumed white Gaussian, $\langle h_i(t)h_j(t')\rangle = 2D\delta_{ij}\delta(t-t')$ with $i,j = 1,2,3$ and using the fluctuation-dissipation theorem (FDT), $D$ is proportional to the temperature $T$ and inversely proportional to the volume $V$, $D = 2k_B T/(|\gamma|M_s V)$[11]. However, as we have shown in[10], in the presence of a bias voltage

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the FDT is strictly not applicable unless we restrict our region of interest to frequencies close to the FMR frequency of the system. In the following, we assume that FDT is still applicable. $\mathbf{m}_{ref}$ is the direction of the magnetization in the RL. The current $I_s = I + i\, sin\,(\Omega t)$ has one static component and another one with frequency $\Omega$. The form of the spin torque in the presence of ac currents still has the same form as in the Slonczewski equation. Zhu et al.[12] calculated the ac spin torque in a magnetic tunnel junctions and found it to be very close in form to the static case. Among other things, they found that at low frequencies, the total spin torque can become less than the spin torque of the static component of the current. Hence an ac current can introduce a partial self-cancellation of the spin torque. Therefore we expect the ac spin torque to affect the noise spectrum of a magnetic system in a nontrivial way. The noise or spectral density functions of the system are calculated numerically since for time dependent systems the fluctuation dissipation relations are invalid[10]. The current flows along the z-direction perpendicular to the xy plane of the magnetic layers. The magnetization of the RL is fixed along the x-direction. The FMR frequency for this system is around 4.5 $GHz$ and $M_s = 1400\ emu/cc$. The constant $p = 100\ Oe/mA$. In magnetic recording,e.g., such devices operate at frequencies below the FMR frequency and hence this system is considered noisy to be useful as a sensor. One possible way to address this problem is to seek a way to suppress the noise for frequencies less than $1.0\ GHz$ and may be shift the noise to higher frequencies which is outside the operational range of the device. In this sense we are selectively suppressing the noise below the FMR frequency only. Previous applications of stochastic resonance were interested in suppressing the noise around the frequency of the driving force which is usually the signal to be measured.

From Fig.4, we observe that it is the x-component of the magnetization of the FL that is the noisiest and hence this would interfere with the GMR signal. The out-of plane z-component of the magnetization is very quiet due to the demagnetization field. Fig. 5 shows that the source of the noise is from the switching of the magnetization between two configurations. One with an average x-component of about 430 $emu/cc$ and the other less stable one with an average x-component around 580 $emu/cc$. The spectral noise in the y and z components show more than the usual FMR peak since the system is not in equilibrium. The higher order harmonics are due to non-homogeneity of the magnetization, i.e., spin waves.

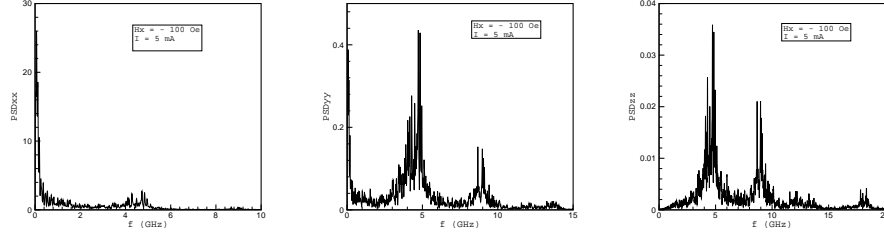In fig. 6, we change the sign of the current to show the effect of the spin torque on the

FIG. 4: The noise spectrum in the x-component of the magnetization of the FL in the absence of ac current: 1) x-component 2) y-component 3) z-component. The x-component component of the magnetization shows significant low frequency noise compared to the other components. The major two peaks in the y and z components are due to the inhomogeneous two states in the system.

magnetization and noise. In this case, the magnetization spends almost equal time in both states. This suggests the use of the spin torque itself as a regulator of the transition rate between two bistable states. In this letter, we will not pursue this idea further and instead we want to explore the idea of adding a strongly periodic current in addition to the dc bias current in order to suppress the noise for frequencies below $1.0\,GHz$.
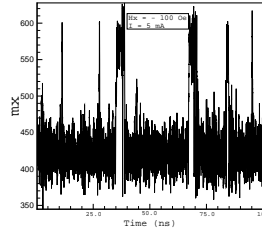


FIG. 5: The x-component of the magnetization as a function of time. The behavior of the average x-component indicates that the magnetization is switching between two states, one stable and the other is unstable (a saddle point).

Figure 7 shows the result of applying an ac current with amplitude equal to the bias current and a frequency of about $8\,GHz$ for the same system of fig. 4. The noise spectrum for frequencies below $1\,GHz$ is greatly suppressed by this additional current source. However now the peak around the FMR frequency is much more pronounced and so does its width. The second narrow peak is that of the ac current. A closer look at the real time behavior of the x-component of the magnetization, fig. 8, implies that the original energy barrier is no longer present. The strong periodic current which in turn induces a periodic spin torque
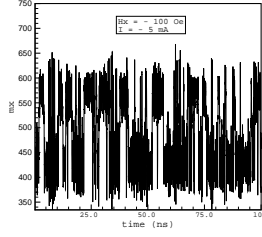
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FIG. 6: The x-component of the magnetization as a function of time for opposite sign of the dc current in fig. 5. The spin torque appears in this case to change the topology of the energy surface to one where both states are equally visited by the magnetization.

is driving the system and making it less sensitive to random thermal fluctuations which are the source of the low frequency. To be an effective suppressant, the frequency of the torque has to be outside the bandwidth of the sensor device.
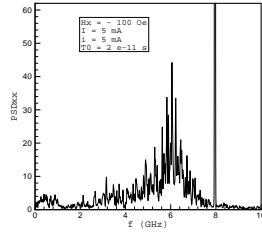


FIG. 7: The noise spectrum in the x-component of the magnetization of the FL in the presence of an ac component to the current with same amplitude as the dc part. The low frequency part of the spectrum has been completely suppressed by the addition of the ac current. The peak at $8\,GHz$ is that of the ac current.

Finally, fig. 9 shows that an increase in the frequency of the ac current degrades the effectiveness of the ac current component to suppress the low frequency noise. We found for this example, that for current amplitudes at $5\,mA$, the maximum frequency the current should have is about twice the FMR frequency of the system. This latter criterion seems to depend strongly on the energy surface and hence there is no universal behavior as in the bistable one dimensional well where the frequency of the driving force is the inverse of twice the inter-well transition time.

In summary, we have shown that the ideas of SR are still attractive even for complex systems which can not be described by a one dimensional potential. In higher dimensions
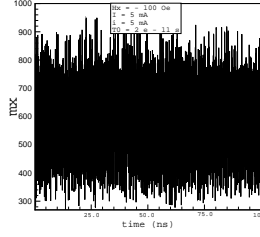
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FIG. 8: The noise spectrum in the x-component as a function of time in the presence of the ac current. The energy surface in this case appears to have only one stable minimum and no switching is observed. The noise in the x component has been pushed to high frequencies.
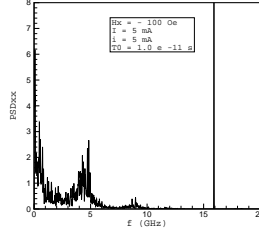


FIG. 9: The noise spectrum in the x-component of the magnetization of the FL. The frequency of the ac current has been doubled compared to fig. 7.

and in the presence of a spin torque, saddle point states become available to the system and may invalidate the ideas of stochastic resonance. In this letter, we showed that a strongly periodic current can suppress thermally induced jumps between a stable and a metastable state and hence suppresses the low frequency noise and enhance the FMR peak in the spin valve.

*This work is based on work done in the Fall of 2004 at Seagate Research and will not be published elsewhere. It is merely a compilation of numerical observations. The author hopes to convince others that there is an interesting interplay of noise and time-dependent spin torques in CPP spin valves that is worth exploring in a more systematic way than attempted here.*

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